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Research paper

An integrated supply chain: A large scale complementarity model for the biofuel markets

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A B S T R A C T

Sometimes, a new technology can have a significant impact on other technologies and existing processes. The planning and implementation of certain policies in order to adapt these new technologies with existing processes is essential. Advanced hydrocarbon (drop-in) biofuel production is an emerging technology that has the potential to influence the existing petroleum supply chain and thus change the equilibrium quantity and prices. This paper addresses a large scale multi-period complementarity model for an advanced hydrocarbon biofuel supply chain integrated with existing petroleum refineries. Market players include suppliers, convertors, deconstruction operators, storage operators, transportation operators and emission auctioneer as well as consumers. The model is multimodal combining multiple transportation modes, seasonal, and other data regarding the current situation of the market, and all the players are assumed to be perfectly competitive. This model simultaneously optimizes the supply chain design and finds the equilibrium quantity of feedstocks, crude oil and final products in the integrated supply chain. Although the main focus of this article is on the mathematical formulation, the numerical simulations for a real case study for Iran are illustrated. This demonstrates the effectiveness of the model in studying the effect of different scenarios on the current supply chain of crude oil based derivatives.

1. Introduction

The only near-term renewable energy source that can provide a liquid fuel, as a substitute for refined petroleum products on the demand side, without the need to replace existing infrastructure, is believed to be biomass. However, deriving the full range of current petroleum products from biomass is the prerequisite for substitution of petroleum products by biofuel [1]. A wide variety of biomass resources can produce biofuel that leads to reduction in the dependence on fossil fuels [2]. The emergence of the third generation biofuel technologies leads to advanced biofuels being produced from cellulosic biomass such as crop residues, wood residues or dedicated energy crops [3]. In addition, functional equivalence of advanced hydrocarbon biofuel products such as cellulosic-biomass-derived gasoline, diesel and aviation fuel with oil derivatives appears to be achievable in the near future [4]. Taking all these promising features into account, one can predict development of the hydrocarbon biofuel industry in the next couple of years. A prerequisite for this is designing and developing cost-effective biomass-to-biofuel supply chains [1]. Nonetheless, there is no obvious immediacy regarding finding an optimal solution to these problems due to their possible interaction with the petroleum products supply chain.

The design and planning of traditional biofuel supply chains have been frequently studied from various aspects, for instance, feedstock selection [5], facility location and capacity design [6], technology selection [7], feedstock seasonality [8], feedstock storage [9], multi-objective model addressing economics, financial risk [10], sustainability [11], and social impact [7]. Using the existing petroleum infrastructures to their fullest has been neglected by these models making their results seem less than promising.

On the other hand, the possibility of converting biomass into biofuel in the traditional refinery is being explored and investigated

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by some researchers, such as [12], and is reported by the U.S. Department of Energy [1]. Moreover, the opportunity of integrating emerging advanced hydrocarbon biofuel supply chains with existing petroleum based production and distribution infrastructures has already been pointed out by Refs. [1] and [13]. These opportunities are supported by government incentives to accelerate bioenergy industry growth. The U.S. Department of Energy [1] is investigating three possible insertion points into the traditional refinery that can have a considerable impact on the optimal transportation network. In the first insertion point, they mix bio-slurry with crude oil; then, send it to crude distillation units and via a series of upgrading units, convert it to gasoline, diesel and jet fuel. In the second point, they could directly send bio-oil to the upgrading units to produce biofuels. The third point includes blending biofuels with conventional fuels in petroleum refineries and sending it to customers through existing pipeline distribution networks. In keeping with these insertion points, the comprehensive management and simultaneous optimization of supply chains of both advanced hydrocarbon biofuels and petroleum products are essential. Taking the supply chain point of view, there are a limited number of studies that explicitly address the economic evaluation of the integration possibilities such as [4,14,15].

There are also additional issues such as storing concepts and structural differences between the supply chains which reinforce the value of studying them concurrently. Generally, many conventional petroleum product networks are based on centralized energy planning and they have been catering mainly to meet urban and industrial needs [16]. However, decentralized energy planning is a suitable alternative for biofuel supply network design in the rural regions owing to the distributed nature of biomass [17]. The complexity of biofuel and petroleum derivative supply chains is due to their supply and distribution networks respectively. The network design models in biofuel supply chains focus on finding the optimal locations for the biofuel plant, considering highly dependency of biomass on geography. On the other hand, this issue in petroleum product supply chains is usually focused on consumer dispersion. These realities show the different nature of these two distinct, but interrelated supply chains.

Nevertheless, there are some considerations which make a centralized decision in the integrated supply chain ineffective. Liberalization and privatization in both advanced hydrocarbon biofuel and oil based supply chains result in decentralization of energy planning. So each agent or player would have their own decision model. Also modeling external, but at the same time influential agents, such as the European Union through its Emission Trading System (ETS) and the governments through their roles in subsidizing biofuel development, has a considerable effect on strategic and tactical level decisions. Therefore, developing a model which considers this issue would be highly valuable. It should be mentioned that a lot of attention has been paid to environmental shortcomings recently, and most governments have started employing environmental preservation regulations [18]. Moreover, the issue is recognized as an influential determinant in performance evaluation of many supply chains [19,20]. So that makes it important to have a capable model to evaluate environmental based scenarios.

Lastly, biomass supply's seasonal and geographical fluctuation is one of the main characteristics of biofuels supply chain [10]. On the other hand, it is possible to shift feedstocks, intermediates and fuels between different seasons within a year. Since, there is an overlap between the supply chains on the demand side, the optimal location, capacity, and type of storages are influenced by the current facilities in the petroleum products supply chain.

Based on the abovementioned points, in spite of the existence of many interdependencies between advanced hydrocarbon biofuel and oil based fuel supply chains, they are very different from the social, economic, and even political points of view. Although the social and political aspects are the main drivers in development of advanced hydrocarbon biofuel supply chains, the economical aspect is the main barrier. However, the limitations to grow a biofuel industry in the future can be addressed by its integration with the existing fossil fuel supply. This effectively creates an opportunity to reduce costs. From the mathematical point of view, equilibrium models are proven to be especially important for modeling different liberalized/liberalizing markets with many distinct players who have their own objective functions. In addition, equilibrium models are capable of analyzing the pricing scenarios in energy markets given their ability and flexibility to manipulate and constrain both primal variables (e.g. biomass production, fuel flow) and dual variables (e.g., prices) together. Therefore, in order to help assure the economic viability of the biofuel industry, it is time to develop an equilibrium model which addresses existing issues in the literature simultaneously. This type of quantitative model facilitates investigating the impacts of the emerging biofuel revolution and the policies emanating from it, on the current hydrocarbon supply chain and would be very handy in supporting policy development and business strategies.

This paper is organized as follows: The formulation method applied in this paper is summarized in Section 2 and then the detailed description of the problem is described in Section 3. Section 4 presents the players' optimization problems and market-clearing conditions as well as the validation method of the model programming. Section 5 clarifies the data set and the implementation of the equilibrium model on the case study of Iran in addition to concluding remarks. In Appendix A, the components of the mixed complementarity model, market clearance and the Karush–Kuhn–Tucker (KKT) conditions, are provided. Lastly, the notations used in the paper are presented in Appendix B.

2. Mixed complementarity problems

In equilibrium modeling, the mixed complementarity problem (MCP) extends the Non-linear Complementarity Problem (NCP) class and allows other bounds lower than zero as well as upper bounds to the variables for which we are looking for solutions. Suppose we have a function F: $R^n \rightarrow R^n$, the MCP(F) is to find a $z \in R^n$ so that for all i:

$$\begin{aligned} z_i \in (l_i, u_i) \quad &\Rightarrow \quad F_i(z_i) = 0 \\ z_i = l_i \quad &\Rightarrow \quad F_i(z_i) \geq 0 \\ z_i = u_i \quad &\Rightarrow \quad F_i(z_i) \leq 0 \end{aligned} \tag{1}$$

where i=1…n and l_i and u_i provide the lower and upper bounds on z_i, respectively. These conditions are often written compactly as $0 \leq F_i(z_i) \perp z_i \geq 0$ with the "perp" operator ⊥ denoting the inner product of two vectors equal to zero. In MCP, the KKT conditions of the players' specific optimization problems are used in order to formulate the model. The KKTs and dual variables correspond to the functions F and vectors z respectively. The KKTs provide the first order conditions for solutions to certain types of problems, in particular optimization problems that fulfill certain conditions such as convexity. For extensive descriptions on various complementarity problems applicable in the field of energy, the readers are referred to [21].

3. Problem statement

Since the supply chain networks require cooperation of different players at the upstream, midstream and downstream echelons along the supply chain, selection of players and partners in the